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Volume I

INVESTIGATION OF LASER SHOCK
PROCESSING -- EXECUTIVE SUMMARY



BATTELLE'S COLUMBUS LABORATORIES
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21. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objective of the program was to demonstrate that laser shock processing is a viable method of improving the fatigue and crack growth performance of mechanically fastened joints. It was shown that a decrease in crack growth rate can be achieved under specified conditions. These conditions involve compressive residual stress (induced by the process) which modify the crack shape and reduce the stress intensity factor. 2024-T3 aluminum alloy reacted		
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20. better to the process than 7075-T6 aluminum. Results were better in thin (.125 inch) than thick (.250 inch) material. Initial design environmental and cost studies indicate that a laser shock processing system for use on a production line is feasible.

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FOREWORD

The research reported herein was conducted by Battelle's Columbus Laboratories for the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. The work was performed under Contract No. F33615-78-C-3217 Project No. 2401 from July 1978 to October 1979. Dr. Frank D. Adams was the Air Force Program Director.

Contractor personnel contributing to the program were Mr. S. C. Ford, Program Manager and Co-principal Investigator, Dr. B. P. Fairand, Co-principal Investigator, Dr. A. H. Clauer, and Mr. R. D. Galliher. The program was centered in the Structural Materials and Tribology Section of the Transportation and Structures Department. Special thanks are extended to Dr. L. E. Hulbert for his assistance in the preparation of the final manuscript. This report was submitted by the authors on August 13, 1980.

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EXECUTIVE SUMMARY

INTRODUCTION

In the early 1970's, Battelle's Columbus Laboratories developed and began reporting upon a process for the improvement of material properties through the imposition of high-intensity laser induced shock waves. During this early work, it was shown that the yield strength and hardness of aluminum alloys were increased up to 30 percent after laser shocking, and weld zones in aluminum alloys could be strengthened to parent material values. Metallurgical studies showed that the laser shocking plastically deformed the microstructure of treated alloys.

In 1977, some investigatory work done at Battelle's Columbus Laboratories showed that the life of fastened-joint specimens could be improved by the use of this process and that crack-growth rates also could be reduced. The fastened-joint tests dealt with specimens which failed by surface fretting, and the test results indicated that the surface hardening characteristics of laser shocking significantly retarded the fretting effects.

In the fall of 1978, Battelle undertook a contract with the U.S. Air Force Flight Dynamics Laboratory, under the direction of Dr. Frank D. Adams. The objective of this program was to demonstrate that laser shock processing is a viable tool for increasing time to crack initiation, decreasing crack-growth rate, and improving the fatigue performance of mechanically fastened joints. The work was carried out beginning in July of 1978 and concluded in August, 1979. The work was essentially conducted in two phases. The first phase involved an extensive fatigue test program with both virgin and laser shock processed test specimens. The second phase was initiated in April, 1979, when some of the test data could not be explained using the then-current theories. Phase II was directed towards a closer examination and understanding of the strength enhancing mechanism which is inherent to the laser shock process.

The basic approach used in this program was to obtain crack initiation/growth data for normal precracked specimens made from 7075 and 2024 aluminum alloys in two sheet thicknesses (0.125 and 0.250 inch).

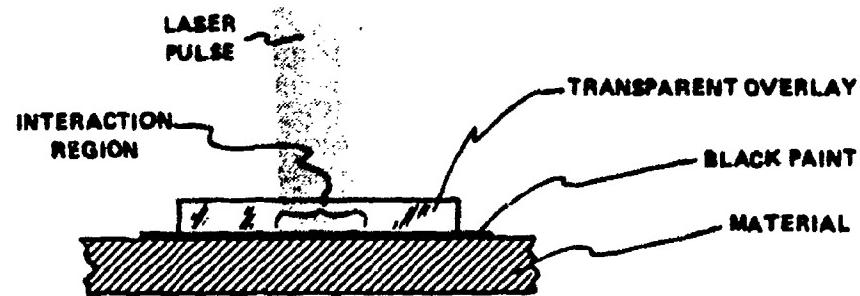
Tests were conducted using both constant-amplitude and modified European standard fighter flight spectrum loads. In addition, low-load-transfer fastened-joint specimens were tested under spectrum loading. A preliminary design, cost and environmental impact analysis was conducted for a simulated production laser shock system. In addition, fractographic and residual stress work to investigate the failure and mechanistic aspects of the process was completed. The detailed results of this program are reported in AFWAL-TR-80-3001, Volume II. The following discussion describes the basic findings and conclusions of this research effort.

DISCUSSION

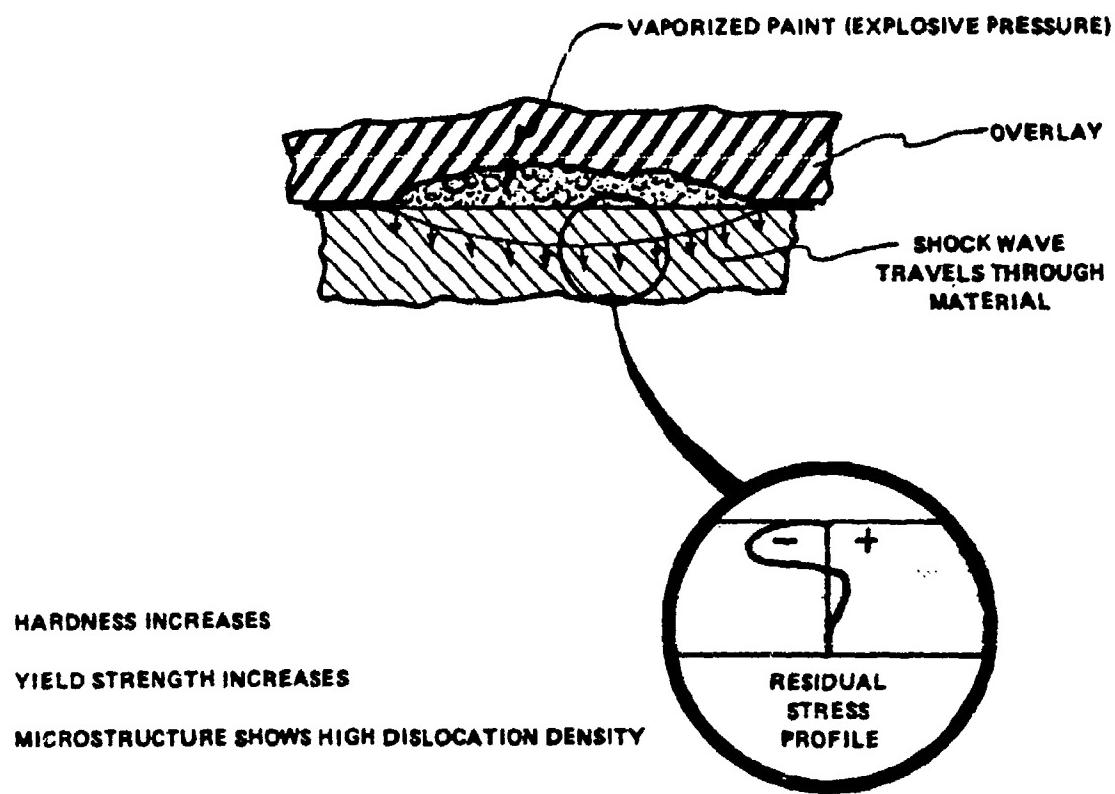
Laser shock processing uses the radiation emitted by a high-power pulsed laser to generate a short-duration (less than 1 millionth of a second) high-amplitude pressure pulse at the surface of the material. It changes the metal's microstructure and stress state, which is the source of the observed improvements in material properties. Generation of the high-amplitude stress wave needed to improve the fatigue properties in aluminum alloys requires covering the surfaces to be shocked with a thin layer of black paint to enhance absorption of the laser radiation and protect the surface from melting and vaporization. A material which is transparent to laser light is placed on top of the black paint. The surface of the black paint is vaporized when it is struck by the laser radiation. The vaporized gas is trapped between the specimen surface and the transparent overlay. During further expansion by absorbing heat from the laser beam, the pressure increases to extremely high levels causing a pressure pulse to react against the specimen surface and then travel through the metal in the form of a shock wave. The overlay acts to confine the vapor and enhance the amplitude and duration of the pressure pulse acting on the surface (see Figure 1). The peak pressures generated at the surface of the aluminum targets are a function of the incident laser power density and the properties of the transparent overlay. The process takes place so rapidly, with vaporization so confined to a small layer, that no significant specimen heating occurs (as opposed to a continuous beam laser). Indeed, the process might well be described as ultrahigh energy shot peening.

Battelle's high power neodymium-glass laser was used in all of the laser shock experiments. This system, which consists of a Q-switched oscillator, followed by six amplifier stages, delivers about 200 joules of laser energy. Water was used as the transparent overlay for this program. The experimental setup is shown in Figure 2.

Specimens were first laser shocked and then subjected to a constant amplitude or modified FALSTAFF flight spectrum loading. Specimens included plates of .125 or .250 inch thickness and low load transfer fastened joints. Some specimens were fatigued to develop fatigue cracks before being laser shocked.



a. Laser shocking setup



b. Schematic of the vaporization and pressure reactions at the metal surface during laser irradiation

Figure 1. The laser shock process

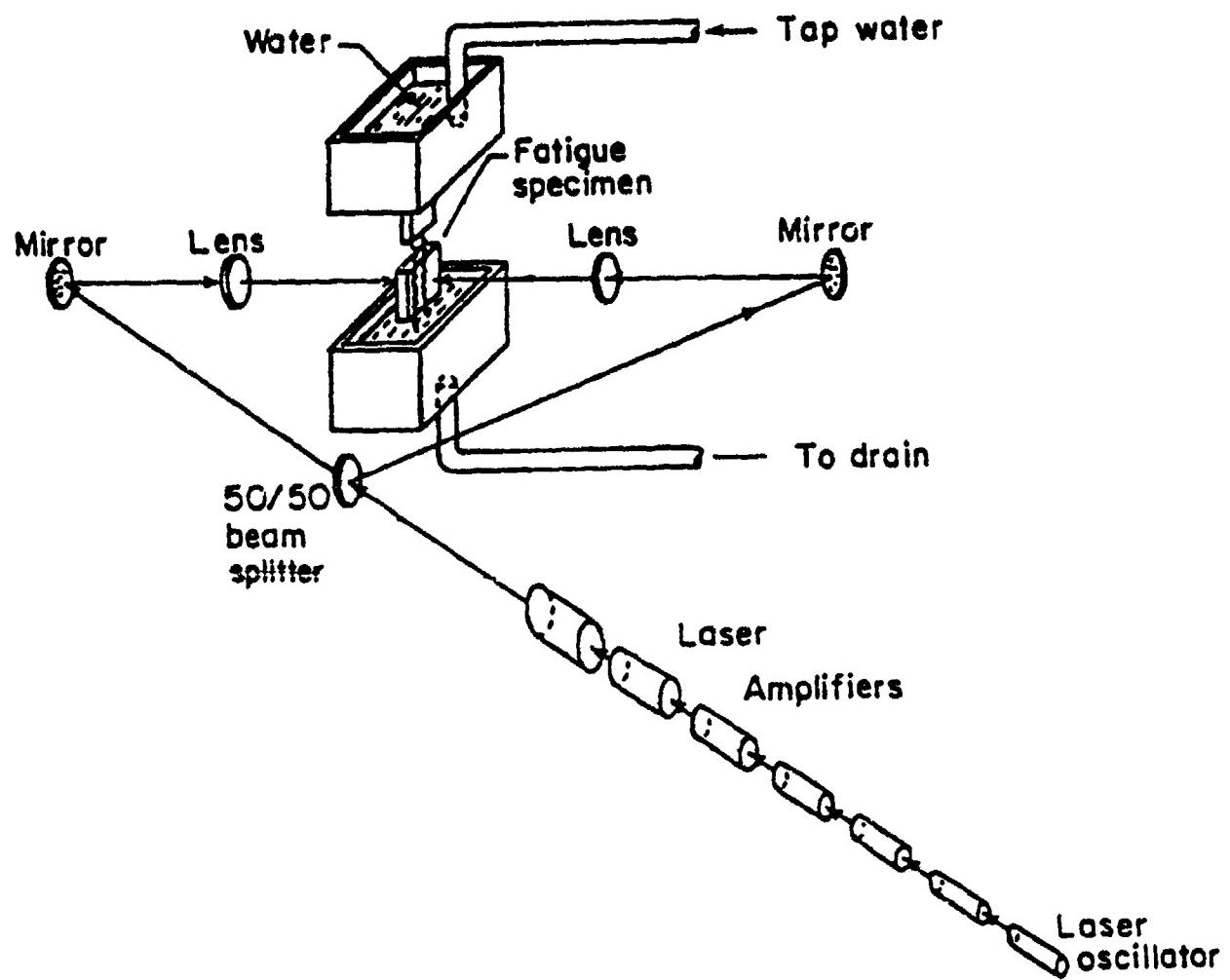
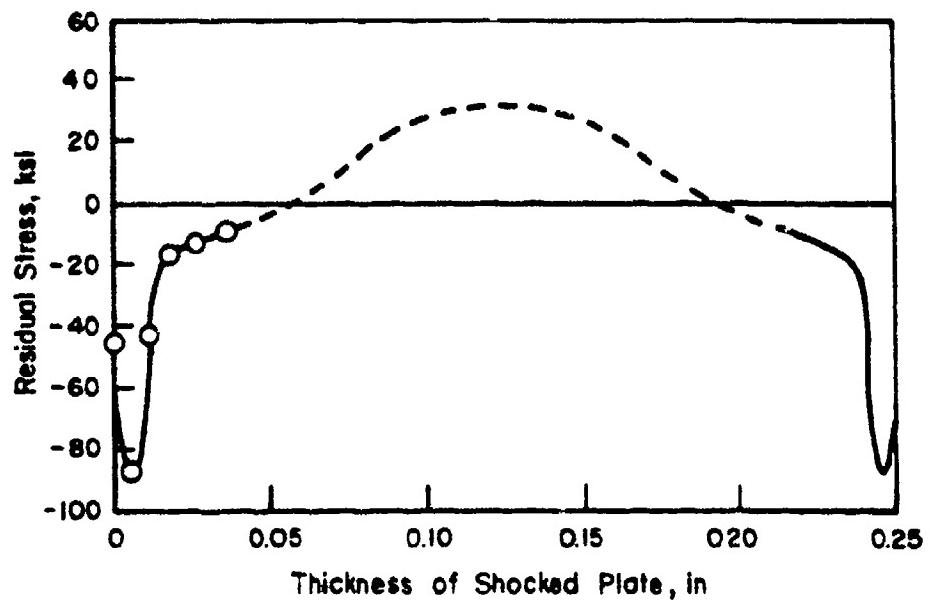


Figure 2. Laser setup and water flow system

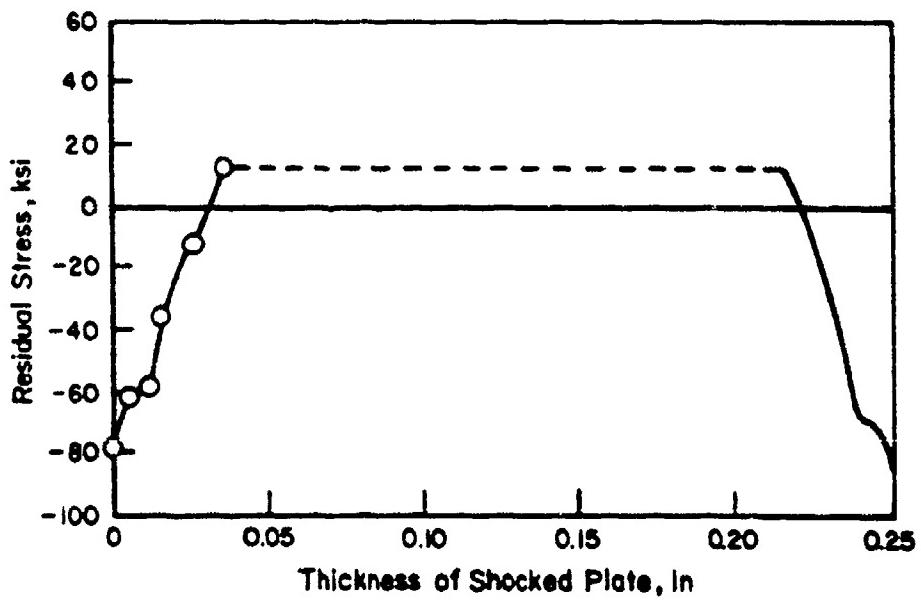
Two aluminum alloys were investigated in the program (7075 and 2024). The results of the tests showed, in general, that fatigue life was not improved for 7075-T6 alloy in the .250 inch thickness but was improved for the .125 inch thickness. However, the fatigue tests showed that the laser shock treatment significantly reduced crack-growth rate and dramatically increased the fatigue life in 2024-T3. The reason for the unexpected difference in the results for the two alloys appears to be because of the ability of the 2024 alloy to absorb higher levels of plastic strain. Evaluation of the data generated on the program raised several questions concerning the failure mechanisms and causes for differences in the appearance of failed surfaces. As a result, the effort was expanded (Phase II) to provide information on the failure mechanisms from a qualitative evaluation of the fracture surfaces and from residual stress measurements made in laser shocked specimens. In addition, the effect of a different transparent overlay material and more intense laser shock conditions on enhancement of fatigue properties was investigated.

Because of Battelle's strong interest in the laser shock process and past commitment to its development, additional fastened-joint experiments were also conducted at Battelle's expense to determine the improvement in fatigue life of 7075-T651 laser treated specimens which were tested at a peak stress level less than that employed on the Air Force program. The lower stress level is representative of the stress environment experienced by cargo aircraft whereas the higher stress level used on the Air Force program may be considered more applicable to fighter aircraft. Results of the Battelle-supported experiments showed that the life of these laser shocked 7075 specimens tested at the lower stress level was a factor of 2-3 greater than unshocked specimens, whereas the higher stress level tests had shown no improvement due to laser shocking. Since fastened joint tests were only conducted with 7075 material, no data is available for the 2024 alloy.

One of the most revealing aspects of the program was the residual stress measurement results for the 7075 alloy. As can be seen in Figure 3, extremely high compressive residual stresses are generated at the surface of a laser shocked specimen. These stresses are balanced by tensile stresses in the midthickness of the specimen. If such tensile stresses occur at the edge of a hole in midthickness, then one would expect crack initiation to occur earlier than in the unshocked specimen which has no tensile residual stresses. Such could be the case for the particular laser shock conditions



a. Hole drilled before shocking at Site 3



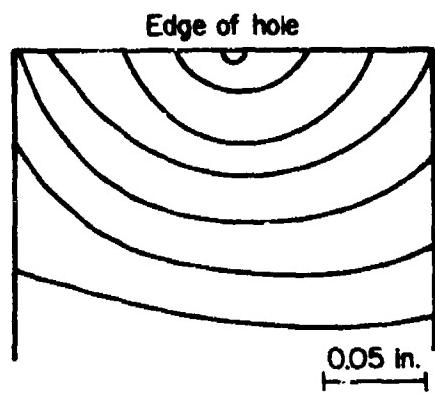
b. Hole drilled after shocking at Site 4

Figure 3. Possible tensile stress distribution in the mid-thickness region of the shocked specimens

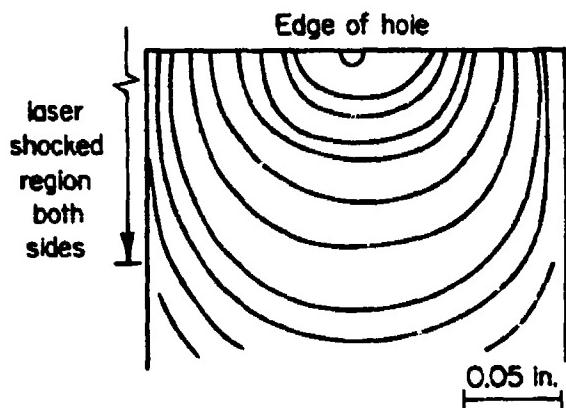
used in this program. Therefore equivalent or extended crack-propagation life and time to failure for the shocked specimens implies that the crack-propagation rate for a laser shocked zone is substantially reduced from that of a nonshocked zone. In fact, the data suggest that the crack-propagation rate is reduced by about one order of magnitude or more.

Study of the fracture surfaces revealed the probable cause for slower crack-propagation. Crack initiation occurred near the midthickness of the specimen and grew normally until it approached the outer 30 to 50 thousandths of material thickness. At this position, the crack had to travel through a high compressive residual stress zone and it was very difficult for the crack front to penetrate that zone. As a result, the crack tended to tunnel and grow in an elliptical manner beneath the surface. This phenomena is seen graphically in Figure 4, which shows the crack fronts for fatigue test specimens which were, (a) unshocked and (b) shocked on both sides. The result of this forced constriction of the crack front would be to slow the crack propagation rate. By changing the laser shocking conditions to modify the distribution of the residual stresses it could be possible to inhibit both crack initiation and crack propagation. This could have an even greater impact on the fatigue life after laser shocking.

There are some problem areas which must be dealt with prior to making this process routinely applicable to aerospace structures. A concern is the fact that the crack initiates early and propagates below the surface in a tunneling manner as shown schematically in Figure 4. Since the mechanism of the process is controlled by residual stresses, it is believed that there are a number of ways to retain the positive aspects of the process while preventing crack-growth rate in a subsurface manner. For example, an annular region around the hole could be laser shocked, excluding the edge of the fastener hole, thus leaving no residual tensile stresses at the edge of the hole in the midthickness. Or, one might investigate the feasibility of generating the compressive stresses at the midthickness with surface being in a tension mode. In this case, cracks would initiate at the surface where they could be detected but penetrate the midthickness only with difficulty, thereby significantly retarding the crack propagation rate. In addition, the possibility of treating the surface of the hole in addition to the surface of the sheet material should be investigated since by inducing beneficial compressive stresses at the surface of the fastener hole, crack initiation could be inhibited along with crack propagation. This could significantly improve fatigue life after laser shocking.



a. Unshocked



b. Shocked both sides

Figure 4. Fracture surface crack front contours

In summary, the major findings of the program may be detailed as follows:

- The presence of residual stresses caused by laser shock processing of aluminum alloys is expected to cause early initiation of crack propagation. This causes a substantial reduction in crack growth rate due to crack configuration modification.
- The total life to failure is improved by nearly one order of magnitude for 2024 aluminum alloys.
- The total life to failure is not substantially affected by laser shocking for 0.250-inch-thick 7075 specimens.
- The presence of residual stresses provides a reduction in crack growth rate for thinner (0.125 inch) sections of 7075 material compared to thicker (0.250 inch) sections.
- Laser shocked 7075 aluminum specimens subjected to spectrum loading showed a reduction in crack-growth rate (factor of 2 to 3) as compared to constant-amplitude tests. This is probably due to the number of low-load levels in the flight spectrum.
- Low-load transfer fastened-joint specimens of 7075 aluminum at 40 ksi maximum load in flight-by-flight conditions showed no improvement due to shocking but additional tests at a maximum load of 27 ksi showed a factor of 2 to 3 improvement due to shocking.
- An environmental assessment of the laser shocking system indicates that: ozone production will have to be controlled (probably by flowing nitrogen over the flash lamps); vaporized target material will have to be trapped and carried away; and the sound of laser shocking will have to be absorbed.
- Preliminary design analysis shows a production laser shocking processing system to be feasible.
- Cost analysis of preliminary designs of neodymium-glass and iodine lasers suggest a cost/shot range of \$0.065 to \$0.38, depending upon the system selected.

It is concluded that not all aluminum alloys are equally benefited by the laser shock parameters imposed in this program. However, a greater understanding of the mechanism of the laser shock process has been obtained,

along with very encouraging results which show a substantial decrease in fatigue-crack-growth rate.

The understanding of the mechanism of the laser shock process provided by the residual stress and fracture studies provides some very positive conclusions concerning the results of this program. Since MIL-A-83444 (Airplane Damage Tolerance Requirements) requires aerospace design engineers to assume that a crack exists in all critically stressed structures, the existence of a process which provides orders of magnitude decrease in crack-growth rate is, indeed, a concept worthy of additional investigation and development. It is, therefore, recommended that investigatory work on this process and its application to aerospace structure be continued.